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MEASUREMENTS OF PLANETARY ELECTRIC CURRENTS

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SOME years ago[1] I suggested that steady electric currents originating in the Earth's core might just be detectable at the surface of the Earth. Such leakage currents, if measurable, would convey important information about the distribution and intensity of those causing the main geomagnetic field.

The existence of such currents is inherent in theories which ascribe the field to a self-exciting dynamo process. Elsasser[2] pointed out the importance for geomagnetism of the reciprocity between the magnetic and electric vectors in electromagnetic theory. The magnetic field $\boldsymbol{H}$ is expressible in the form of a vector potential $\boldsymbol{A}$ by the equation:

$$\boldsymbol{H} = \operatorname{curl} \boldsymbol{A}$$

Because the gradient of any scalar function can be added to $\boldsymbol{A}$, it is possible to express $\boldsymbol{A}$ in terms of two scalar functions ψ_E and ψ_M. In dealing with magnetic fields in a spherical shell or sphere, this is done by forming from these scalars a vector along the radial direction and one at right angles to it, that is:

$$\boldsymbol{A} = \boldsymbol{r}\psi_E + \boldsymbol{r}\wedge\nabla\psi_M$$

This separation has physical significance, for the magnetic fields corresponding to the two terms, called the magnetic and electric modes, are generated in different ways. The electric mode, $\boldsymbol{H}_E$, is given by:

$$\boldsymbol{H}_E = \operatorname{curl}\ \boldsymbol{r}\,\psi_E = -\boldsymbol{r}\wedge\nabla\psi_E$$

and consequently consists of lines of forces wrapped round spherical surfaces. The current, $\boldsymbol{J}_E$ (in E.M.U.), giving rise to such a field is:

$$4\pi\boldsymbol{J}_E = \operatorname{curl}^2 \boldsymbol{r}\psi_E = \nabla\left(\frac{\mathrm{d}}{\mathrm{d}r}\, r\,\psi_E\right) - \boldsymbol{r}\nabla^2\psi_E$$

and therefore has radial components.

On the other hand, the magnetic mode field $\boldsymbol{H}_M$ has radial components.

$$\boldsymbol{H}_M = \operatorname{curl}\boldsymbol{r}\wedge\nabla\psi_M = -\operatorname{curl}^2 \boldsymbol{r}\psi_M = -\nabla\left(\frac{\mathrm{d}}{\mathrm{d}r}\, r\psi_M\right) + \boldsymbol{r}\nabla^2\psi_M$$

Bullard[3] has shown that a sphere rotating inside a conducting spherical shell in a magnetic mode field generates an electric mode field, and he gave reasons for supposing this to occur in the Earth's core, as its angular velocity

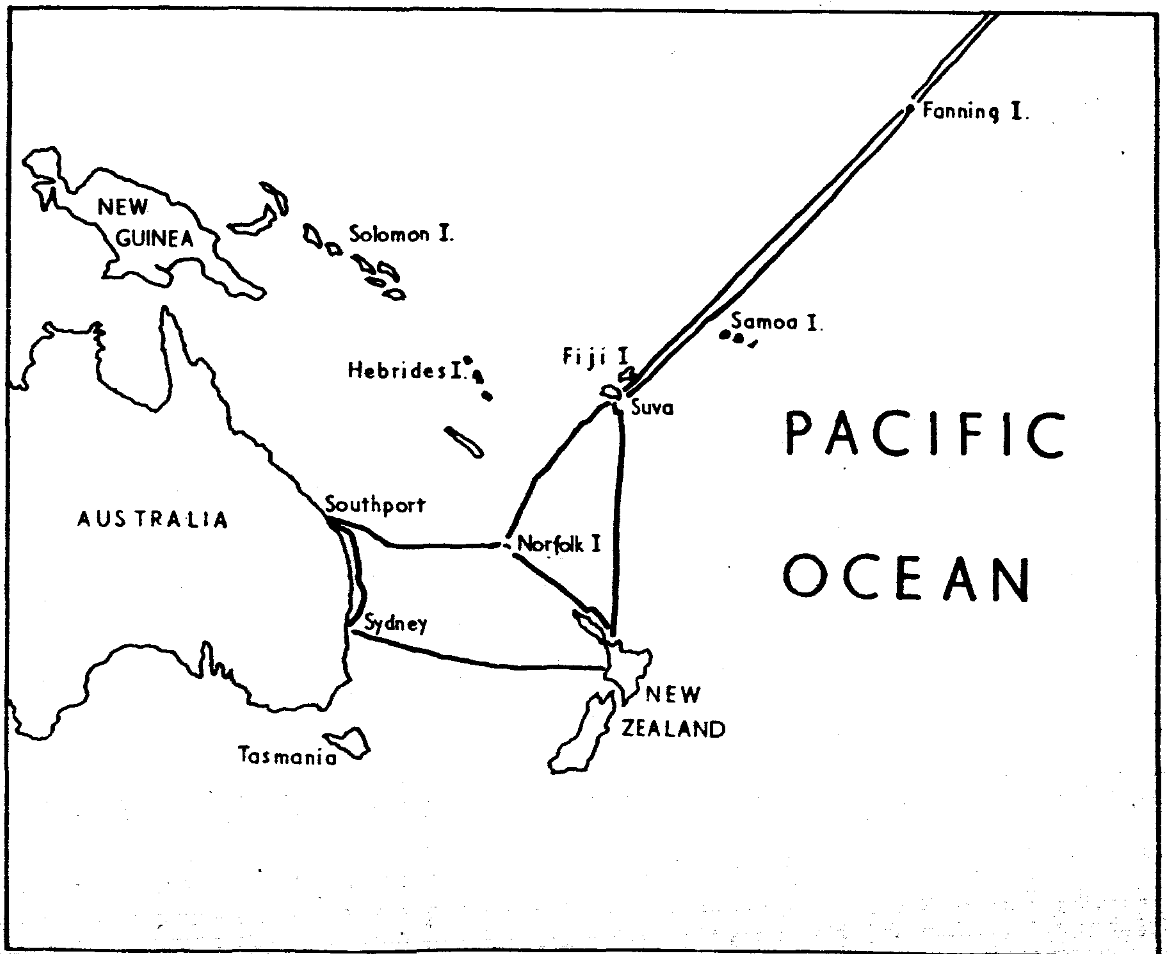

Fig. 1

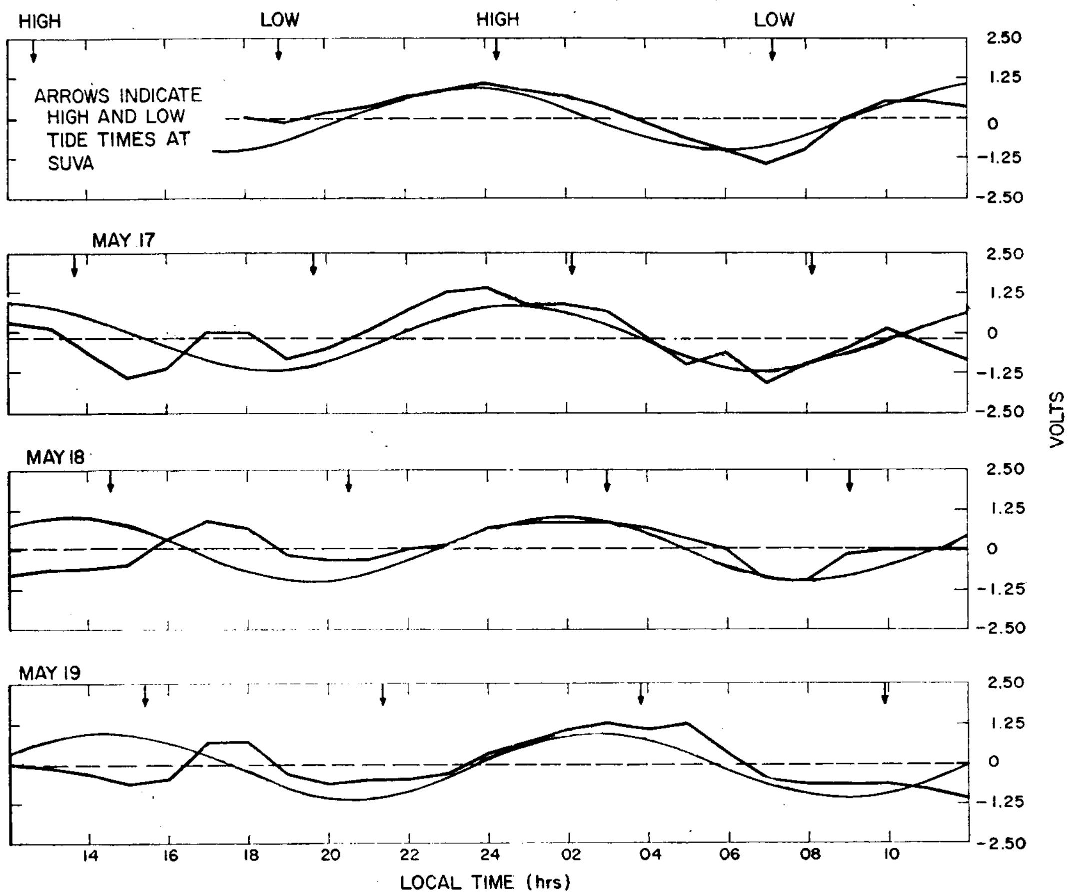

Fig. 2. Suva–Auckland cable (hourly averages)

varies with radius. I have shown[1] that an electromotive force on the core-mantle boundary generates an electric mode field. In general one can say that in a spherically symmetrical body, it is difficult to see why current should flow solely around the Earth's axis as is necessary to generate the dipole field, as Schuster[4] first pointed out when he was searching for a cause of geomagnetism. Consequently strong electric mode fields are an essential assumption in the theory of the Earth's magnetic field, and a direct proof of their existence is most desirable.

I argued quantitatively[1] for a mantle of uniform conductivity, and Roberts and Lowes[5] proved, more generally, that, assuming the electrical conductivity to fall off monotonically with radius, the electric current leaking to the surface from the electric mode in the core is probably measurable. The potential gradient is of the order of 0·1–1 mV/km throughout the mantle.

The detection of steady Earth currents over distances of the order of 1 km is not possible, as the contact potentials between the electrodes and the Earth cannot be controlled to the necessary accuracy. The chance of carrying through this experiment successfully has therefore had to await the opportunity recently presented by the abandonment of the telegraph cables in the Pacific.

Fig. 1 shows the cables which have been used in preliminary experiments carried out last spring by the courtesy of Cable and Wireless, Ltd., London, and the Overseas Telecommunications Commission of Australia, Sydney. Each cable consists of a central conductor surrounded by an insulator protected by a wire sheath. At each end an additional insulated conductor is run out to sea and attached to the sheath between 2 and 8 miles. By means of these 'sea earths' it is possible to earth both ends of each cable, sufficiently far from the land to minimize chemical disturbances, so that it may reasonably be supposed that the contact potentials at each end of the cable are constant and nearly equal. By measuring the current between one end of the main cable and the sea earth it is possible to measure the potential difference between the Pacific at either end.

It was expected that the geomagnetic daily variation would induce in the ocean a fluctuating electromotive force containing periods of 24 h, 12 h, etc. (for the part of the daily variation depending on the lunar day is only one-twentieth of that depending on the solar day). Inspection of the first results, however, showed a dominant component of a period of half the lunar day (12 h 25 min). It must be concluded therefore that the motional induction resulting from the oceanic tides outweighs the induction due to the geomagnetic daily variation.

An order of magnitude argument supports this interpretation. The height of the equilibrium oceanic tide is about 1 ft. The vertical component of the tidal velocity is therefore about 10^{-3} cm/sec. The horizontal velocity components are larger by the ratio of the wave-length of the tide divided by the depth of the ocean (of the order of 10^4). The horizontal velocity (v) is 10 cm/sec and the electric field generated is vZ (where Z is the vertical component of the geomagnetic field) or 10^{-8} V/cm. This value, 1 mV/km, is of the order of that observed.

The electromotive force induced by the lunar oceanic tide will, of course, be a pure sine wave with a period half the lunar day T_L (24 h 50 min). That induced by the solar oceanic tide and the geomagnetic daily variation (neglecting the lunar component of the latter) will be a non-sinusoidal, periodic function $f(t)$ of a solar day (T_S), but perturbed by effects of geomagnetic disturbances $D(t)$.

Thus the observed variation of potential difference between the ends of each cable for each day V_1, V_2 can

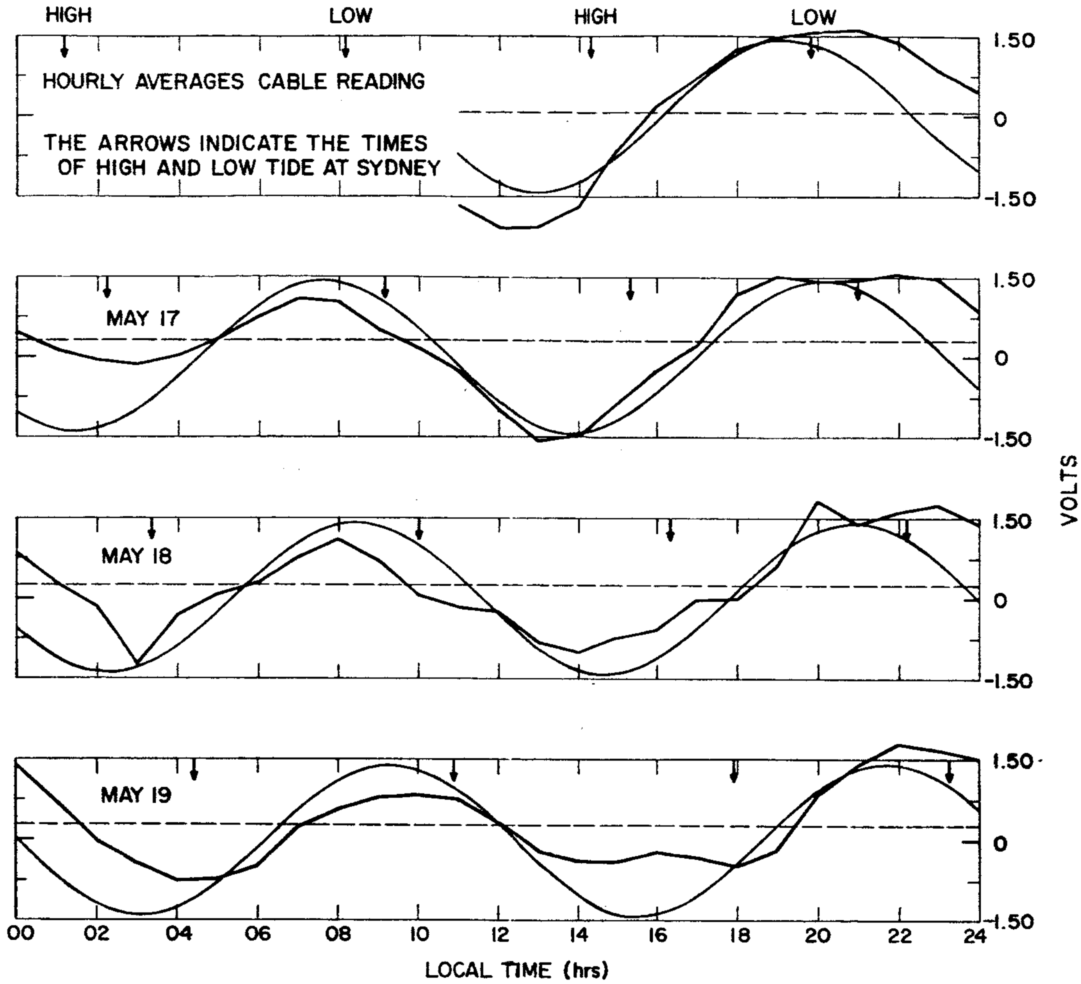

Fig. 3. Sydney–Auckland cable (hourly averages)

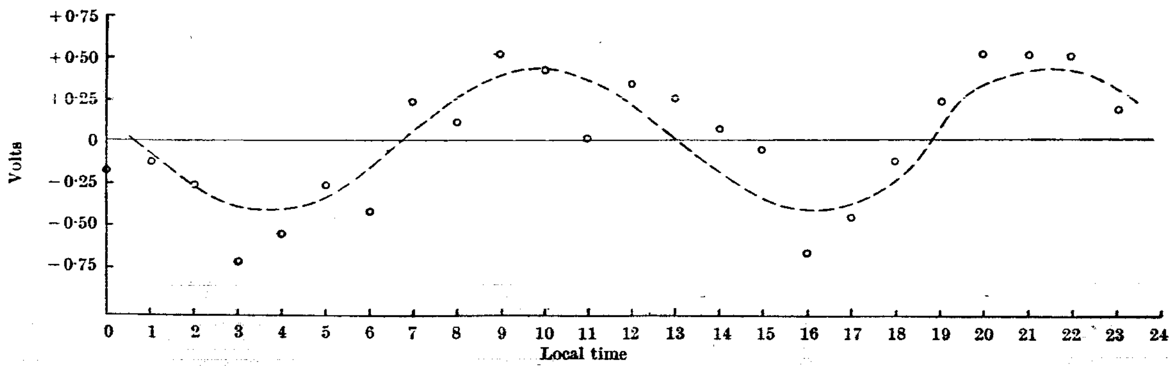

Fig. 4. Suva–Auckland cable, May 16–20, 1963. Average differences

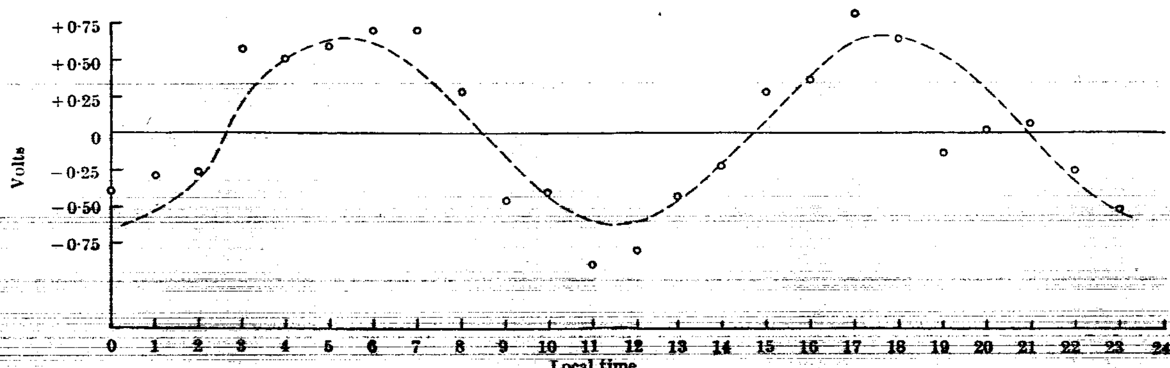

Fig. 5. Sydney–Auckland cable, May 16–20, 1963. Average differences

be expressed by the relations, where A and a are the amplitude and phase of the tidal induced effect:

$$V_1(t) = A \sin 2\pi(2t/T_L + a) + f(t) + D_1$$
$$V_2(t) = A \sin 2\pi[2(t + T_S)/T_L + a] + f(t + T_S) + D_2$$

The method of analysis therefore consisted in subtracting the values at the same hour from the records for two adjacent days.

Thus:

$$V_1 - V_2 = -2A \sin 2\pi T_S/T_L \cos 2\pi(2t/T_L + a + T_S/T_L) + D_1 - D_2$$

In averages of such differences taken over a number of lunar days the disturbances will tend to be eliminated.

Fig. 2 shows the measurements of earth currents made on the Suva–Auckland cable during May 16–19 and Fig. 3 on the Sydney–Auckland cable during May 16–19. The results plotted are the averages over each hour. The differences between the results for adjacent days are determined as described here and the average differences over the days are shown by full lines in Figs. 4 and 5 (Suva–Auckland and Sydney–Auckland cables respectively). To these curves is fitted a sinusoidal wave of period $T_L/2$, shown by dotted lines in Figs. 4 and 5. The amplitude of this wave is divided by $2 \sin 2\pi T_S/T_L$ to give A. Its phase enables a to be found. Hence the currents due to the lunar oceanic tide can be compared with the observed readings. These are shown each day by the thin lines on Figs. 2 and 3. It is clear that, at least on magnetically quiet days, the main currents arise from the ocean tides.

It will be seen that the current induced directly by the quiet-day daily variation is less evident. As the tidal effects are exactly sinusoidal the mean potential differences for many days should be a good measure of the steady electric currents flowing. On the limited amount of material so far available it appears that they are no more than 0·1 mV/km.

The extension of these observations which will be shortly undertaken should provide an interesting study of the tides in the middle of the ocean. It will be seen from the figures that there is a phase relation between the Earth currents and the tidal heights. Were the tides standing waves, the velocities would be zero at high and low tides. But, as the latter occur when the potential differences are numerically greatest, the tides in this area are progressive waves. These not widely suspected motional induction effects in the oceans may make appreciable contribution to the geomagnetic variations observed on the continents.

I thank Mrs. L. Broglio for help with the analysis of these results, and Mr. D. J. Moore of Cable and Wireless, Ltd., Suva City, and Mr. J. D. Wood of the Overseas Telecommunications Commission of Australia, who made the recordings. I also thank Mr. D. Scott of Cable and Wireless, Ltd., London, and Mr. W. W. Jenvey of the Overseas Telecommunications Commission of Australia, whose co-operation made it possible to carry out these observations.

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